

Spin asymmetry for proton-deuteron Drell-Yan process with tensor-polarized deuteron

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Tensor structure of the deuteron can be studied by deep inelastic scattering and Drell-Yan process to understand it in terms of quark and gluon degrees of freedom. It probes interesting features in the deuteron including a D-wave contribution. In the charged-lepton DIS, twist-two structure functions b_1 and b_2 are expressed by tensor-polarized parton distribution functions (PDFs). We note that the HERMES experimental measurement of b_1 seems to be much different from a conventional theoretical prediction. This puzzling situation should be significantly improved in the near future by an approved experiment to measure b_1 at JLab. On the other hand, the tensor-polarized PDFs, especially antiquark distributions, could be measured by spin asymmetries in the Drell-Yan process with a tensor-polarized deuteron at Fermilab. In this work, we estimate tensor-polarization asymmetries for the Fermilab Drell-Yan experiment by using a parametrization for the tensor-polarized PDFs to explain the HERMES b_1 data. Obtained spin asymmetries are typically a few percent order and they could be measured by the Fermilab-E1039 experiment. Since the tensor-polarized antiquark distributions will play an important role to solve the puzzle, further theoretical and experimental efforts are needed toward the Drell-Yan experiment at Fermilab and other hadron facilities.

I. INTRODUCTION

Deuteron structure has been studied by hadron degrees of freedom. The deuteron is a bound state of proton and neutron mainly in S wave. In fact, the experimental magnetic moment of deuteron supports the S-wave idea, whereas the existence of a finite electric quadrupole moment indicates that the deuteron should also contain D wave. Therefore, the deuteron is an S-D mixture state, and the D-wave contribution is very small so as to be consistent with the magnetic and quadrupole moments.

It is interesting to investigate the tensor structure in terms of quark and gluon degrees of freedom. About 10 years ago, the HERMES collaboration made the first measurement of the tensor structure function b_1 for the deuteron [1]. However, the measurement shows that b_1 is much larger than the convolution-model prediction with the S-D mixture [2–5]. It indicates that the tensor structure of deuteron is not understood in the parton level. There are other theoretical works on the deuteron b_1 by including shadowing phenomena, pions, and hidden-color state [6–9].

There is an approved experiment to measure b_1 by the electron deep inelastic scattering (DIS) at JLab (Thomas Jefferson National Accelerator Facility) and it will start in a few years. This accurate experiment will help us to understand the tensor structure of deuteron. The structure function b_1 is expressed by the tensor-polarized parton distribution functions (PDFs); however, the separation of antiquark distributions is not obvious solely from the DIS measurements. Since the understanding of the

tensor-polarized antiquark distributions could be essential for clarifying the discrepancy between the conventional theory and the HERMES data, it is important to measure them experimentally. Fortunately, it is possible in the Fermilab-E1039 experiment by the Drell-Yan process with a tensor-polarized deuteron target. The purpose of our research is to calculate the tensor-polarized spin asymmetries of the Drell-Yan process [10] because there was no theoretical estimate to be used for an experimental proposal and future comparison with the data.

II. TENSOR STRUCTURE FUNCTIONS IN DIS WITH POLARIZED DEUTERON

The tensor structure of the deuteron can be investigated in charged-lepton DIS with the polarized deuteron, and it is shown in the Fig. 1. The hadron tensor of the

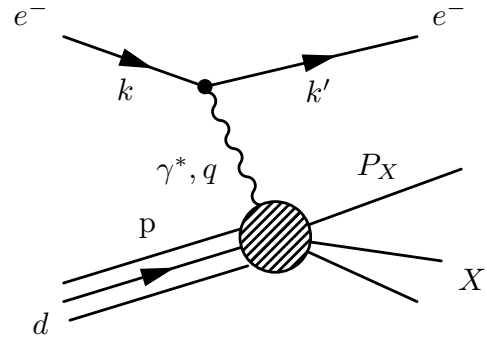


FIG. 1: Deep inelastic scattering with polarized deuteron.

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deuteron is defined as

$$\begin{aligned}
W_{\mu\nu}^{\lambda_f \lambda_i} &= \int \frac{d^4x}{4\pi M} e^{iqx} \langle p \lambda_f | J_\mu(x) J_\nu(0) | p \lambda_i \rangle \\
&= -F_1 \hat{g}_{\mu\nu} + \frac{F_2}{M\nu} \hat{p}_\mu \hat{p}_\nu + \frac{ig_1}{\nu} \epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma \\
&\quad + \frac{ig_2}{M\nu^2} \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p \cdot q s^\sigma - s \cdot q p^\sigma) \\
&\quad - b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\
&\quad + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}). \quad (1)
\end{aligned}$$

where M , p , and q are deuteron mass, deuteron momentum, and virtual-photon momentum, λ_i and λ_f indicate spin states of the deuteron, and the details of other notations are found in Refs. [2, 11].

There are eight structure functions in Eq. (1). The structure functions F_1 , F_2 , g_1 and g_2 exist in the spin-1/2 nucleon, whereas b_1 , b_2 , b_3 and b_4 are new structure functions for the spin-1 deuteron. In the parton picture, b_1 is expressed by the tensor-polarized PDFs $\delta_T q_i = q_i^0 - (q_i^{+1} + q_i^{-1})/2$, where the superscript $(\pm 1, 0)$ indicates the deuteron spin state and the subscript i is the quark flavor, in the similar way with F_1 :

$$\begin{aligned}
F_1 &= \frac{1}{2} \sum_i e_i^2 [q_i(x, Q^2) + \bar{q}_i(x, Q^2)], \\
b_1 &= \frac{1}{2} \sum_i e_i^2 [\delta_T q_i(x, Q^2) + \delta_T \bar{q}_i(x, Q^2)]. \quad (2)
\end{aligned}$$

If b_1 is integrated over x , it leads to an interesting sum rule for b_1 . Since the tensor-polarized valence-quark distributions do not contribute to this sum, a finite sum should come from the tensor-polarized antiquark distributions [12]:

$$\int dx b_1(x) = \frac{1}{9} \int dx [4\delta_T \bar{u}(x) + 4\delta_T \bar{d}(x) + \delta_T \bar{s}(x)]. \quad (3)$$

Therefore, a nonzero measurement of b_1 integral indicates the existence of finite tensor-polarized antiquark distributions, in the similar way that the Gottfried sum-rule violation indicated a finite $\bar{u} - \bar{d}$ distribution [13]. This was suggested by the HERMES collaboration [1]:

$$\begin{aligned}
\int_{0.002}^{0.85} dx b_1(x) &= [1.05 \pm 0.34 \pm 0.35] \times 10^{-2}, \\
\int_{0.002}^{0.85} dx b_1(x) &= [0.35 \pm 0.10 \pm 0.18] \times 10^{-2}, \quad (4)
\end{aligned}$$

where the first integral is obtained in the measured kinematical range and the second one by imposing the constraint $Q^2 > 1 \text{ GeV}^2$. It should be also noted that the measured HERMES b_1 values are much larger in magnitude than the standard convolution-model estimates, and it may be considered as a deuteron tensor-structure puzzle. In any case, the antiquark distributions can be measured directly in the Drell-Yan process, which could lead clarification of the puzzle.

III. SPIN ASYMMETRY IN THE DRELL-YAN PROCESS WITH UNPOLARIZED PROTON AND TENSOR-POLARIZED DEUTERON

The proton-deuteron Drell-Yan process is schematically shown in Fig. 2, and the hadron tensor is defined as

$$W_{\mu\nu} = \frac{1}{4\pi M} \int d^4\xi e^{-iQ \cdot \xi} \langle p d | J_\mu^{em}(\xi) J_\nu^{em}(0) | p d \rangle. \quad (5)$$

This hadron tensor is much complicated in comparison with that of DIS, because there exists more than 100 structure functions in the polarized Drell-Yan processes. Among spin asymmetries, A_{UQ_0} [14, 15] is the most important asymmetry for probing the deuteron tensor structure, and it is expressed as

$$A_{UQ_0} = \frac{1}{2 \langle \sigma \rangle} \left[\sigma(\bullet, 0) - \frac{\sigma(\bullet, +1) + \sigma(\bullet, -1)}{2} \right], \quad (6)$$

where \pm and 0 are the spin states of the deuteron, and \bullet indicates the unpolarized proton. Namely, the spin asymmetry A_{UQ_0} shows the cross section difference with different deuteron spin states, and it will disappear if the deuteron were in purely S wave. In the following discussions, we show the asymmetry multiplied by the factor of 2 ($A_Q \equiv 2A_{UQ_0}$).

In the parton model, A_Q is related with the tensor-polarized PDFs of the deuteron as

$$A_Q = \frac{\sum_i e_i^2 [q_i(x_1) \delta_T \bar{q}_i(x_2) + \bar{q}_i(x_1) \delta_T q_i(x_2)]}{\sum_i e_i^2 [q_i(x_1) \bar{q}_i(x_2) + \bar{q}_i(x_1) q_i(x_2)]}. \quad (7)$$

At large $x_F (= x_1 - x_2)$, the terms $\bar{q}_i(x_1) \delta_T q_i(x_2)$ and $\bar{q}_i(x_1) q_i(x_2)$ can be neglected in comparison with $q_i(x_1) \delta_T \bar{q}_i(x_2)$ and $q_i(x_1) \bar{q}_i(x_2)$, respectively, and the asymmetry becomes simpler

$$A_Q = \frac{\sum_i e_i^2 [q_i(x_1) \delta_T \bar{q}_i(x_2)]}{\sum_i e_i^2 [q_i(x_1) \bar{q}_i(x_2)]}. \quad (8)$$

Therefore, the tensor-polarized antiquark distributions can be obtained by measuring A_Q , and this is the advantage of using the Drell-Yan process.

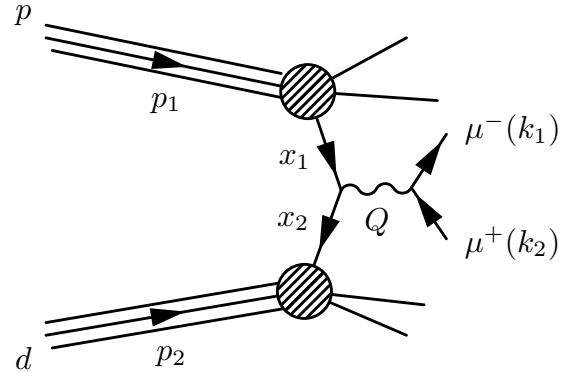


FIG. 2: Drell-Yan process with unpolarized proton and tensor-polarized deuteron.

IV. RESULTS

Here, we present the theoretical estimates for the spin asymmetries $A_Q(x_1, x_2)$ [10] of proton-deuteron Drell-Yan process for the Fermilab E-1309 experiment. In Fig. 2, quark and antiquark annihilate into dimuon through the virtual photon. The dimuon momentum is given by momentum fractions of quark and antiquark (x_1 and x_2) as

$$M_{\mu\mu}^2 = Q^2 = (k_1 + k_2)^2 = x_1 x_2 s, \quad (9)$$

where $s = (p_1 + p_2)^2$ is the center-of-mass energy. In the E1309 experiment of Fermilab, the beam is 120 GeV unpolarized proton of the Main Injector and the target is a polarized deuteron.

In order to obtain the spin asymmetries $A_Q(x_1, x_2)$, the unpolarized PDFs are taken from the MSTW code [16] in the leading order of the running-coupling constant α_s . As for the initial tensor-polarized PDFs, the only available choice is the parameterization [17] based on HERMES data. In this parameterization, two sets are provided in order to find the impact of tensor-polarized antiquark distributions. There are no tensor-polarized antiquark distributions at the initial energy scale $Q_0^2 = 2.5 \text{ GeV}^2$ in set 1, whereas finite tensor-polarized antiquark distributions exist in set 2 even at the initial energy scale. The set-2 parameterization should be more reliable in the sense that it agrees with the HERMES measurements of b_1 . The tensor-polarized distributions at other energy scales can be obtained by the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution equations [2] in the same way with the unpolarized PDFs [18].

We also provide error-band estimates in this work. There are 3 parameters involved in the initial tensor-polarized parton distributions in set 2 [17]. For a physical quantity $f(x)$, its error $\delta f(x)$ is expressed as

$$[\delta f(x)]^2 = \Delta\chi^2 \sum_{i,j} \left[\frac{\partial f(x)}{\partial \xi_i} \right]_{\hat{\xi}} H_{ij}^{-1} \left[\frac{\partial f(x)}{\partial \xi_j} \right]_{\hat{\xi}}, \quad (10)$$

where H_{ij} is the Hessian matrix, ξ_i is a parameter, and $\hat{\xi}$ is the minimum parameter set. Here, we adopt $\Delta\chi^2 = 1$ in showing the error bands. Expanding χ^2 around the minimum parameter set $\hat{\xi}$, we can express $\Delta\chi^2$ by the Hessian matrix

$$\Delta\chi^2 = \chi^2(\hat{\xi} + \delta\hat{\xi}) - \chi^2(\hat{\xi}) = \sum_{i,j} H_{ij} \delta\xi_i \delta\xi_j. \quad (11)$$

In Fig. 3, we show the tensor-polarized PDFs of set 1 at the initial energy scale $Q_0^2 = 2.5 \text{ GeV}^2$ and the evolved scale $Q^2 = 30 \text{ GeV}^2$. The scale 2.5 GeV^2 is the average Q^2 value of the HERMES experiment, and 30 GeV^2 is roughly the average Q^2 value of the Fermilab Drell-Yan experiment. Even after the Q^2 evolution, the tensor-polarized antiquark distributions are very small, since

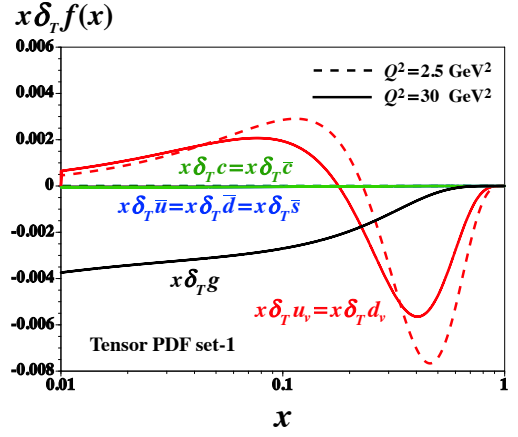


FIG. 3: Tensor-polarized parton distributions at energy scales $Q_0^2 = 2.5 \text{ GeV}^2$ (dashed curves) and $Q^2 = 30 \text{ GeV}^2$ (solid curves) for set 1 [10].

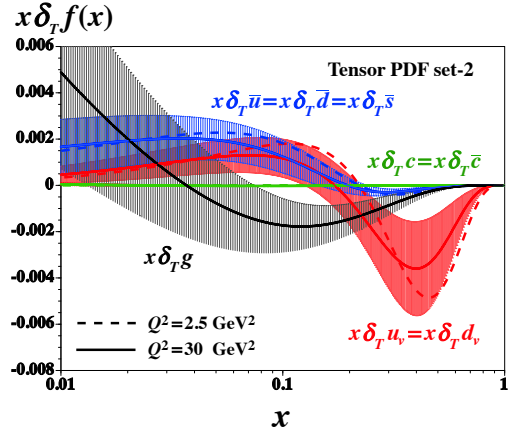


FIG. 4: Tensor-polarized parton distributions with error estimates at energy scales $Q_0^2 = 2.5 \text{ GeV}^2$ (dashed curves) and $Q^2 = 30 \text{ GeV}^2$ (solid curves) for set 2 [10].

they are set to be 0 at the initial scale. Therefore, we have the relationship $\delta_T \bar{u}(x, Q^2) = \delta_T \bar{d}(x, Q^2) = \delta_T \bar{s}(x, Q^2) = \delta_T \bar{c}(x, Q^2)$ in the Q^2 evolution.

The tensor-polarized PDFs of set 2 are shown in Fig. 4 together with error bands. In Figs. 3 and 4, we notice that there also exists the tensor-polarized gluon distribution, even though it is set to be zero at the initial energy scale $Q_0^2 = 2.5 \text{ GeV}^2$. Because the tensor-polarized antiquark distributions are assumed to be equal at the initial energy scale, the relation $\delta_T \bar{u}(x, Q^2) = \delta_T \bar{d}(x, Q^2) = \delta_T \bar{s}(x, Q^2)$ still holds in the Q^2 evolution. With these Q^2 evolved distributions, we are now ready to calculate tensor-polarized spin asymmetries in the Fermilab Drell-Yan experiment.

The spin asymmetries $A_Q(x_1, x_2)$ are shown in Fig. 5 for both set 1 and set 2 at typical momentum fractions $x_1 = 0.2$, $x_1 = 0.4$ and $x_1 = 0.6$ [10]. We find that the spin asymmetries are a few percent for both sets. If x_2 is very small, the differences between the set-1 and the set-2 results are large. This is because the spin asymmetries $A_Q(x_1, x_2)$ are very sensitive to the tensor-

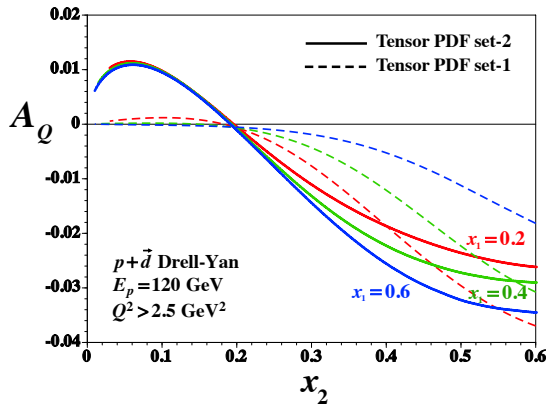


FIG. 5: Spin asymmetries $A_Q(x_1, x_2)$ are estimated at typical momentum fractions $x_1 = 0.2$, $x_1 = 0.4$, and $x_1 = 0.6$. The dashed curves are for set 1 and the solid curves are for set 2 [10].

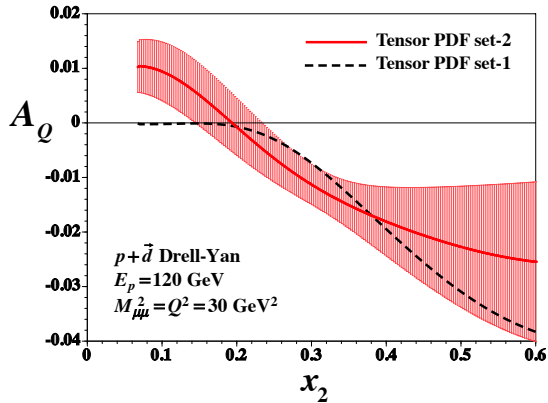


FIG. 6: Spin asymmetries $A_Q(x_1, x_2)$ are estimated at the typical energy scale $Q^2 = 30 \text{ GeV}^2$. The dashed curve is for set 1 and the solid curve is for set 2 [10].

polarized antiquark distributions in this region as indicated in Eq. (8). The set-2 asymmetries should be more reliable since the existence of finite tensor-polarized antiquark distributions is in agreement with the HERMES data.

In order to indicate typical errors of our estimates, we show the asymmetries $A_Q(x_1, x_2)$ in Fig. 6 at the typical energy scale $Q^2 = 30 \text{ GeV}^2$. Even if the error bands are considered, the asymmetries are of the order of a few percent and they obviously deviate from 0. It validates the importance of the Fermilab Drell-Yan experiment to probe the tensor structure of the deuteron, in particular the tensor-polarized antiquark distributions. In addition to the Fermilab-E1039 experiment, such a Drell-Yan experiment is possible at hadron-accelerator facilities such as BNL-RHIC, CERN-COMPASS, J-PARC, GSI-FAIR, and IHEP in Russia. The structure function b_1 can be measured also at the future EIC. The studies of the tensor structure functions will become one of interesting topics of hadron physics in a few years, much theoretical studies are needed to clarify the tensor structure in the quark-gluon degrees of freedom.

V. SUMMARY

The tensor-polarized parton distributions are important physical quantities, and they can reflect interesting dynamical aspects of deuteron including the D-wave contribution. The tensor structure of the deuteron can be studied by DIS and Drell-Yan process, while it is much easier to get the tensor-polarized antiquark distributions in the Drell-Yan process. In this work, the tensor-polarized spin asymmetries A_Q were theoretically calculated for the proton-deuteron Drell-Yan process in the parton model, and we obtained a few percent values. We also found a finite tensor-polarized gluon distribution due to Q^2 evolution. We hope that the Fermilab-E1309 experiment will be realized and a new field of hadron spin physics will be explored in future.

Acknowledgments

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